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Thickness maps of Neogene and Quaternary sediments in the Kloštar Field (Sava Depression, Croatia)

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Abstract

The Kloštar Oil Field is situated at the north-western part of Sava Depression in the Croatian part of the Pannonian basin (CPBS). It is a typical geological structure that evolved through the Neogene and Quaternary. It is why that structure evolution is detailed reconstructed using palinspastic mapping (i.e. using as datum plane selected chronostratigraphic horizons). The total map set includes 6 structural and 15 palaeostructural maps interpolated over five E-log markers and one border. The mapping has been done using the Ordinary Kriging technique. Obtained maps were used for interpretation of geological evolution during the Neogene and Quaternary, and especially description of hydrocarbon reservoirs formation and migration pathways. The structural development can be explained through two phases of transtension and two of transpression that existed regionally in the Sava Depression. However, the maps and cross-section that are described locally show changes of dominant tectonic styles, especially during the Quaternary when the most of the field was a depositional centre.

Key words: palinspastic, Neogene, Quaternary, Kloštar, Sava, Croatia

1. INTRODUCTION

The Kloštar Field is one of the largest hydrocarbon fields in the Sava Depression. Previous results of palinspastical analysis in different regions of the Croatian part of the Pannonian Basin System (CPBS) have been given in several scientific papers, e.g., in Hernitz & Jurak (1973), Hernitz at al. (1980) and Velić et al. (2011). Regarding the Kloštar Field, this is the second comprehensive palinspastic reconstruction of Neogene and Quaternary evolution, which closely follows the result published in Velić et al. (2011). Presented analyses, together with that study, gave the complete set of thickness maps for that field. Therefore, those maps can be used as an interpretation of geological evolution during the Neogene and Quaternary for any larger structure inside the Sava Depression.

2. GEOGRAPHY

The Kloštar Field is located about 35 km east/southeast of the Croatian capital Zagreb, and administratively is part of Zagrebačka County. The field geographically is in the alluvium of the Sava River, i.e. in the Sava Depression (Figure 1), which represents the southwestern margin of the Pannonian Basin System (PBS). The present-day topography is influenced by the Moslavačka gora Mt. (peak is 489 m). Therefore, the surface of the Kloštar structure is located along western slopes of that mountain. The field margins on the surface covers about 30 km^2.

Figure 1: Geographical and regional geological schematic map of Kloštar Field (modified from Velić (2007)

3. GEOLOGICAL SETTINGS

The Kloštar Field is in the western part of the Sava Depression, where hydrocarbon reservoirs are within Miocene sandstones and tectonised Palaeozoic basement schists. Miocene sediments are up to 1600 m thick and transgressive over an unconformity with Palaeozoic magmatites and metamorphites in the base. The complex structural evolution resulted in the formation of 20 reservoirs as independent hydrodynamic units. The total of 172 wells has been completed. The field is anticline, striking northwest-southeast, which also includes the Northern marginal fault of the Sava Depression, which represented the border between depositional areas for Late Pannonian and Early Pontian sandstones. Analyses had been undertaken based on Croatian lithostratigraphic nomenclature (Šimon, 1980) of the Neogene and Quaternary sediments valid for the Sava Depression (Figure 2).

Mapping horizons included marls as key-beds defined on E-logs as markers (from regionally characteristic shapes on apparent resistivity log curves). It is why those marker beds are named E-markers. One “horizon” (named as “Tg”) is in fact the unconformity between the Palaeozoic and Neogene and is consequently names as E-border, i.e. physical border (not marker or key-bed). That is defined as border between very different apparent resistivity values observed on electro logs in top and bottom rocks of unconformity.

The Neogene and Quaternary sedimentary complex was subdivided into three major megacycles (Velić at al., 2002; Velić, 2007). The oldest (1st) megacycle represents the Prečec Formation of Badenian and Sarmatian age. The sedimentary complex is extremely heterogeneous, comprising breccias, conglomerates, sandstones, siltstones, shales, marls, igneous rocks, and limestones. The Prkos, Ivanić-Grad, Kloštar Ivanić, and Široko Polje Formations belong to the 2nd megacycle, i.e., to Pannonian and Pontian stages. Those formations are defined as monotonic alterations of marlstones and sandstone sequences. The 3rd megacycle is represented by the Lonja Formation of Pliocene and Quaternary age. It is composed mostly of unconsolidated sediments, i.e., sands, gravels, loess, and some lignite. Major oil and gas reservoirs are within sandstones the 2nd megacycle.

Figure 2: Formal lithostratigraphic and chronostratigraphic units, E-log markers/border, and absolute ages in the Sava Depression

4. APPLIED DATA SELECTION AND MAPPING METHODOLOGIES

The first part of analysis included structural and thickness maps. The point (hard) data were interpolated with Ordinary Kriging, which had been previously proven as the best interpolator in this field (Balić et al., 2008). The second part was the creation of a longitudinal cross-section across the field's structure, based on Kriging maps. The number of point values (i.e. thicknesses measured in wells) varied from more than 20 for the deepest mapped border („Tg“) to about 120 for the youngest E-log marker (α as border between Miocene and Pliocene).

4.1. Palinspastical reconstruction applied on the Neogene-Quaternary sediments in the Kloštar Field

The term “palinspastic” was introduced by Kay (1937) for a palaeotectonic map in which the features have been restored as nearly as possible to their original positions. Some of the first regional palinspastic reconstructions in the Sava Depression have been reported by Hernitz and Jurak (1973) and Hernitz et al. (1980). The maximum number of palaeostructural maps is defined with:

$$N=(n^2+n)/2 \qquad \text{(Equation 1)}$$

Where:

N - Total number of structural maps that can be derived from the set of available borders;

n - Number of available borders (here borders are E-log markers).

All intervals that could be interpolated in the Kloštar Field are given in Table 1. The six marker/border planes are selected as the top and bottom of formations.

α'-datum plane	Rφ-datum plane	Z'-datum plane	Rs5-datum plane	Rs7-datum plane	Tg-datum plane
	Rφ- α'	Z'- α'	Rs5- α'	Rs7- α'	Tg- α'
		Z'- Rφ	Rs5- Rφ	Rs7- Rφ	Tg- Rφ
			Rs5- Z'	Rs7- Z'	Tg- Z'
				Rs7-Rs5	Tg-Rs5
					Tg-Rs7

Table 1: Interpolated palaeostructural maps in the Kloštar Field (grey are maps given in Velić et al., 2011; orange are maps given in this paper)

Palaeostructural maps can be divided into structural (when the top is present-day relief or datum plane, here +100 m) and palaeothickness maps (when the top and bottom are both in the subsurface). Therefore palaeothickness maps represent thicknesses of unit formed in the past. The structural maps, also kind thickness maps, include top plane still exposed to surface sub-aerial or sub-water present-day processes. Structural and palaeothickness maps of particular lithostratigraphic formations for the Kloštar Field were already published (Table 1-grey shading) in Velić et al. (2011). For this paper, we present additional thickness maps that encompass two or more formations (Table 1 – see orange shading).

4.2. Parameters of applied kriging interpolation

There are two geostatistical approaches (deterministic and stochastic) and many geostatistical techniques that could be applied to mapping of hydrocarbon reservoirs. Each of these methods includes modelling uncertainties, and minimizing them as data increases. Associated with this text are all maps interpolated using the Ordinary Kriging technique (methodology is explained, e.g., in Mathéron, 1965; Hohn, 1988; Isaaks and Srivastava, 1989; Journel and Huijbregts, 1978). The same or similar techniques have been applied in the other parts of the CPBS (Malvić, 2003, 2005; Malvić and Đureković, 2003, 2004; Malvić and Bastaić, 2008; Malvić and Prskalo, 2008) or in the same field (Balić et al., 2008). Variogram models were calculated and approximated with the theoretical model.

5. INTERPRETATION OF SELECTED THICKNESS MAPS

Thickness map Tg-Rs5 (Map 1) represents the Prečec and Prkos Formations. Due to sparse data mapping the thickness of the Prečec and Prkos Formations has been possible only in some areas. The thickness reaches 500 m in the mapped area, but it is mostly in the range of 100 to 300 m.

Thickness map Tg- Z' (Map 2) shows the Prečec, Prkos and Ivanić Grad Formations. The lack of data restricted the mapping of the whole area again. Thickness varies from 250 to 650 m. the distribution of sediments is almost the same as on the previous map.

Thickness map Tg- Rφ (Map 3) represents the Prečec, Prkos and Ivanić Grad and Kloštar Ivanić Formation. The position of the thicker sediments is still similar, i.e. the maximum is again in the central part of the map, but the minimum is now observed on the southeast (previously was on northwest).

Thickness map Tg-α' (Map 4) includes the Prečec, Prkos and Ivanić Grad, Kloštar Ivanić and Široko Polje Formations. The thinner sediments are at the southeastern portion of the field, less than 600 m. The greatest thicknesses, more than 1400 m, are in the central part of the map.

Thickness map Rs7- Z' (Map 5) shows the Prkos and Ivanić Grad Formations. The maximum thickness is in the central part of the map, while minimum thickness values (100-250 m) at located at the northwestern, southeastern, and a portion of the central area.

Thickness map Rs7- Rφ (Map 6) includes the Prkos, Ivanić Grad, and Kloštar Ivanić Formations. Thicknesses vary from 250 to 850 m. The highest value slightly decreases from the northern to central portions of the map. The southern portion is characterized by thinner sediments with a minimum of 250 m in the southeastern corner of the map.

Thickness map Rs7-α' (Map 7) represents the Prkos, Ivanić Grad, Kloštar Ivanić, and Široko Polje Formations. This map shows the greatest thickness changes and displacements along a NW-SE fault line. The maximum thickness is 1400 m and is located at the southwestern portion of the map.

Thickness map Rs5- Rφ (Map 8) shows only the Kloštar Ivanić and Ivanić Grad Formations. Sediments are predominantly 400-550 m thick, with thicker sediments (>600 m) in the north-central portion of the map. The thinnest sediments, a result of faulting, occur near the northwest corner of the map.

Thickness map Rs5-α' (Map 9) is very similar to the Rs7-α' map (Map 7). Those two maps describe the same formations except that Rs7-α' includes the Prkos Formation. The thickness changes and displacements from northwest to southeast are the result of fault activity.

Thickness map Z'-α' (Map 10) describes the Kloštar Ivanić and Široko Polje Formations. It is similar to maps Rs7-α' (Map 7) and Rs5-α' (Map 9). The main northwest-southeast fault caused thickness variations in the central part of the field. That fault divides thicker parts of the unit to the southwest from thinner parts to the northeast.

6. INTERPRETATION OF CONSTRUCTED PALINSPASTIC CROSS SECTION

To display thickness variations along the vertical section (i.e., depth), a palinspastic section is constructed (Section 1). The thickness and elevation data used for constructing the cross-section were well data calculated from E-logs. The northwest-southeast strike of the cross-section (Section 1) is shown on all maps (Maps 1-10). The thickness of the oldest Prečec Formation (Section 1) significantly differs from other formations, especially in the central portion of the section. The Palaeozoic palaeorelief has caused development of a heritage structure (i.e. structures of similar shape to older ones) during the Badenian, Sarmatian, and Early Pannonian. The Early Pannonian Prkos Formation (Section 1) is relatively thin compared with the older Prečec Formation and even with all younger formations. It is a result of the 1st transpressional phase in the CPBS that was active during the Sarmatian (Malvić and Velić, 2011) and obviously also active here during the Early Pannonian.

The overlaying Ivanić-Grad and Kloštar Ivanić Formations (Section 1) were deposited during the period of the 2nd transtension (Malvić and Velić, 2011), i.e., during the deposition of large quantities of sand and silt inside a brackish lake environment. Turbiditic currents represented the main transport mechanisms for such detritus. The two youngest formations (Široko Polje and Lonja Formations; Section 1) are the thickest because of local subsidence. This is interesting result because from the Late Pontian to the end of the Quaternary (recent) there lasted the 2nd transpressional phase, which generally dominated in entire CPBS (Malvić and Velić, 2011). However, locally existed zones of kilometre dimensions that was continuously sinking (e.g., in the Kloštar structure), probably supporting the existence of Pliocene-Quaternary fluvial and marshy environments. This can be clearly observed in the southeastern part of Section 1. In the Lonja Formation the inversion of the structure can be clearly observed, especially on the southeast where almost complete inversion of Early Pontian-Badenian anticline is observed. Interestingly, such young subsidence did not invert all anticlines formed in the Late Miocene, which later trapped hydrocarbons and formed numerous reservoirs.

7. CONCLUSIONS

The purpose of this study was to reconstruct geological events from the development of the earliest Badenian structures in the Kloštar Field, their evolution through Late Miocene and Pliocene, and their eventual structural formation during the Quaternary. Associated maps display classical palinspastic reconstructions, including thickness maps and one characteristic cross-section. The results presented by the maps and cross section can be summarized as:

1. Sedimentation of the oldest Prečec Formation (Badenian and Sarmatian) was mostly influenced by Palaeozoic paleorelief combined with synsedimentary tectonics.
2. The Lower Pannonian sediments of the Prkos Formation are the thinnest as result of extended influence of the 1st regional transpression.
3. The 2nd transtension, with the deposition of reservoir sands, lasted through the Late Pannonian and Early Pontian, but generally structures still maintained some of the morphology of the older palaeorelief. However, in the northwesterrn portion of the maps, inversion of structures (shapes) formed before Late Pannonian was significant.
4. The northwestern part of the structure was again transpressed (2nd transpression) during the Late Pontian.
5. Sedimentation of the youngest Lonja Formation (Pliocene and Quaternary) is characterised by a different style than prevailing transpressional mechanisms throughout most of the CPBS. New depositional areas and a large thickness are observed on the northwest and southeast margins of the field. The older uplifted palaeorelief mostly remained in the northwestern part.
6. The main uplifted zones formed at the end of the Late Pontian and some of them were even inverted on the southeastern margin during deposition of the Lonja Formation.

7. Contemporary hydrocarbon traps formed during the Pliocene and Quaternary. It was also a time of hydrocarbon migration upward due to gravitational separation inside the reservoir rocks (secondary migration).

SOFTWARE

Thickness maps were interpolated in Surfer 8.0, a licensed version bought from Golden Software Inc.

MAP DESIGN

Maps were designed using the Ordinary Kriging interpolation technique and appropriate variograms. Input data, considered as hard data, were interpreted from well depths of electro-log markers, which represented unit boundaries.

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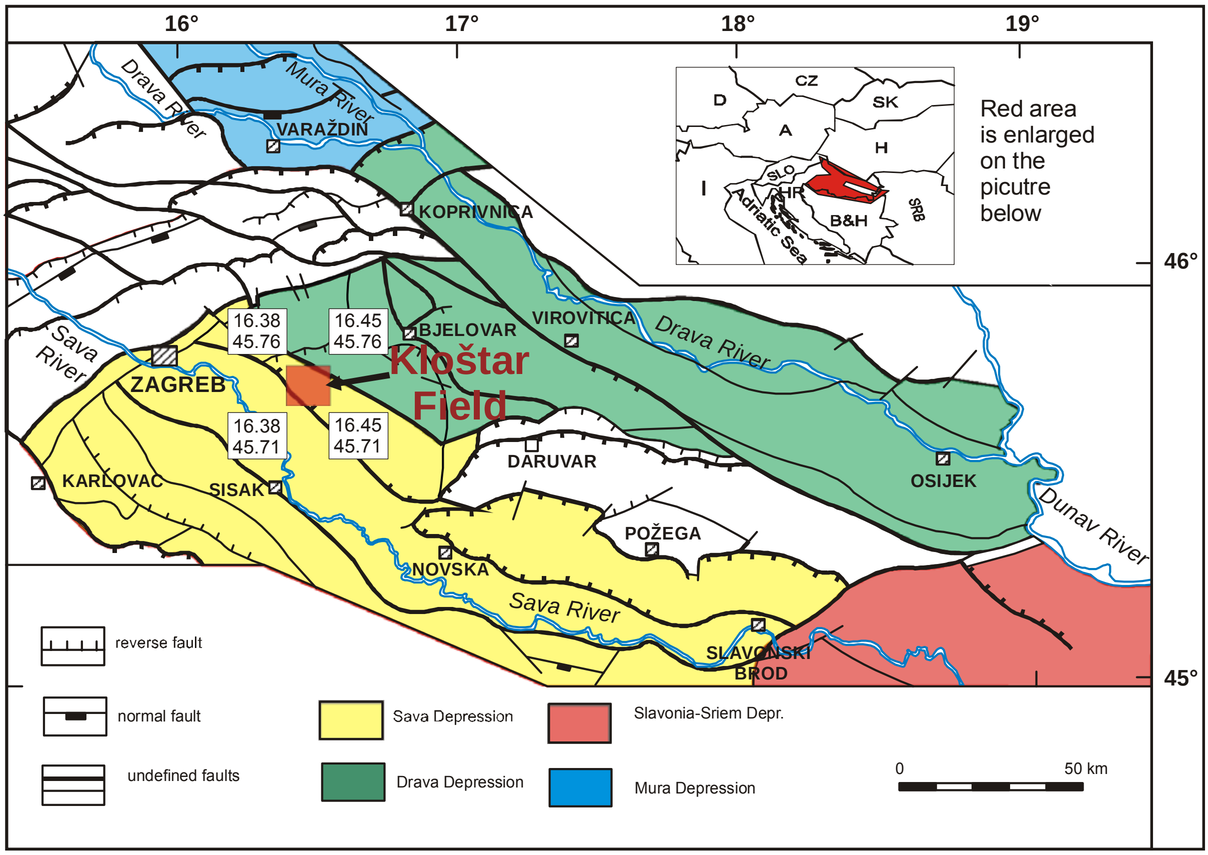

Figure 1: Geographical and regional geological schematic map of Kloštar Field (modified from Velić, 2007)

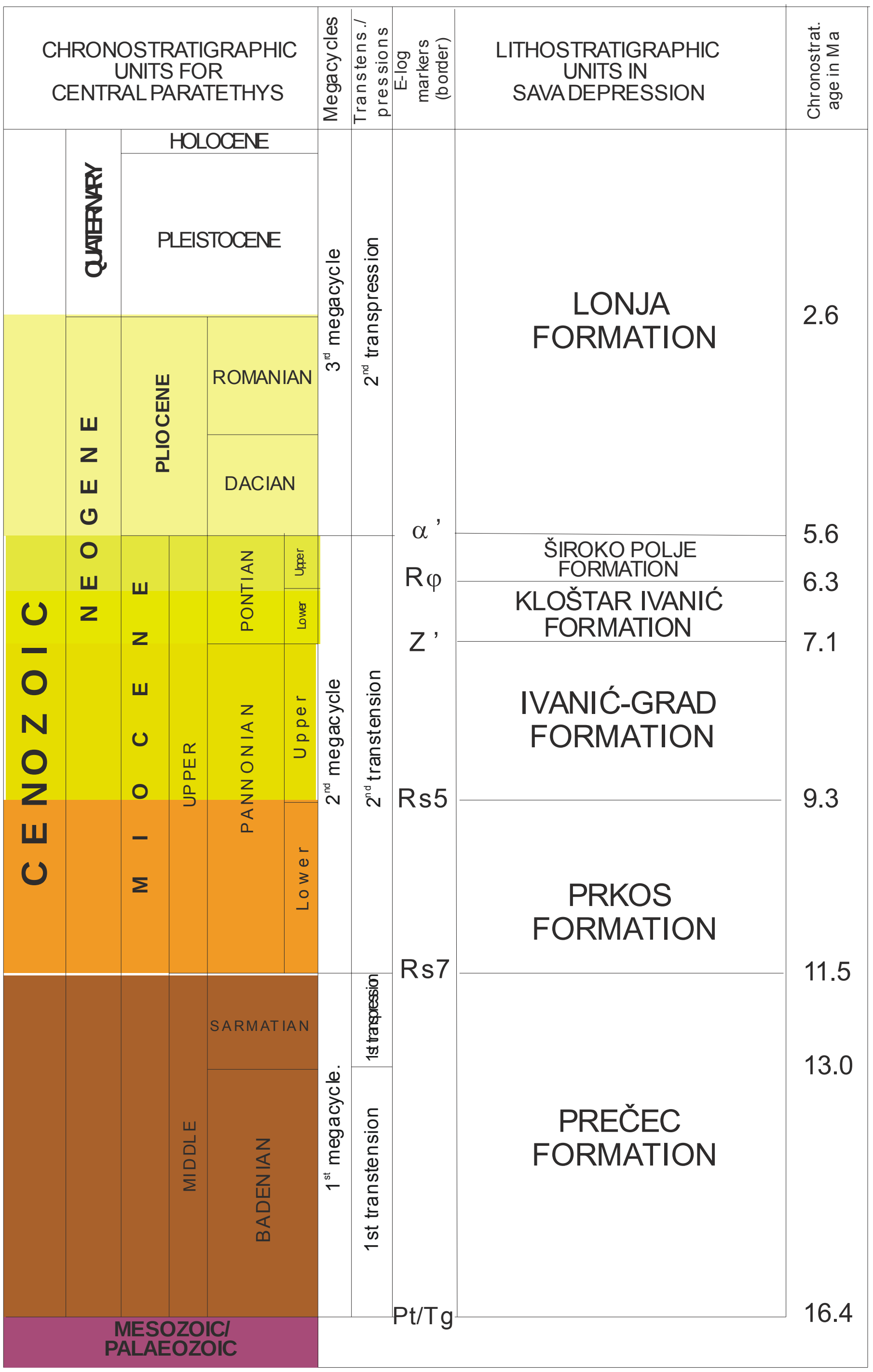

Figure 2: Formal lithostratigraphic and chronostratigraphic units, E-log markers/border, and absolute ages in the Sava Depression

Thickness of Neogene and Quaternary sediments in the Kloštar Field (Sava Depression, Croatia)

Data sources: Jović, G. (2009) Palinspastic reconstruction of Miocene sediments in th Kloštar Oil Field. Unpublished Graduate Thesis, Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb.

Projection: Gauss-Krueger (zone 6)

Drawing datum plane: +100 m

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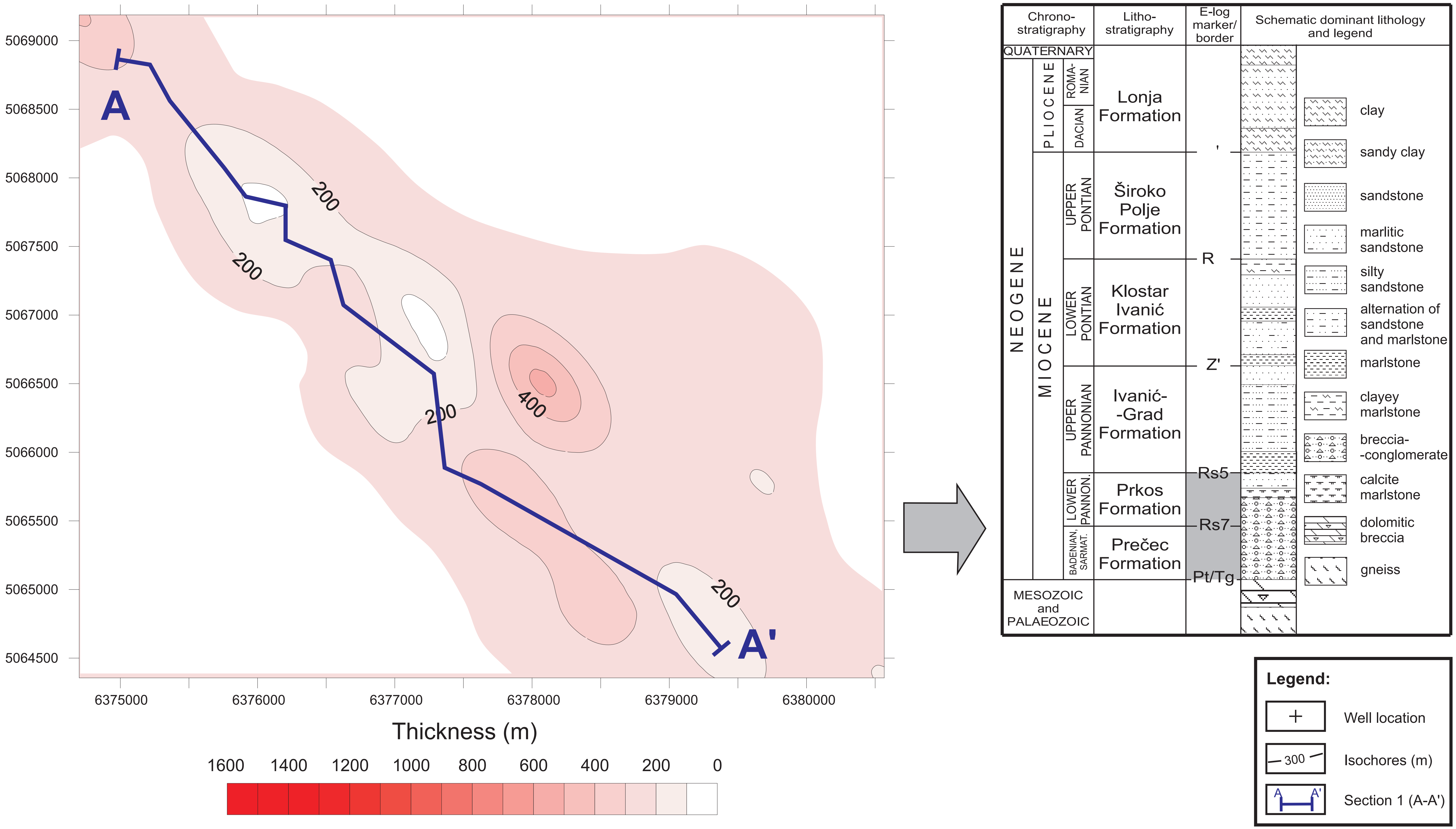
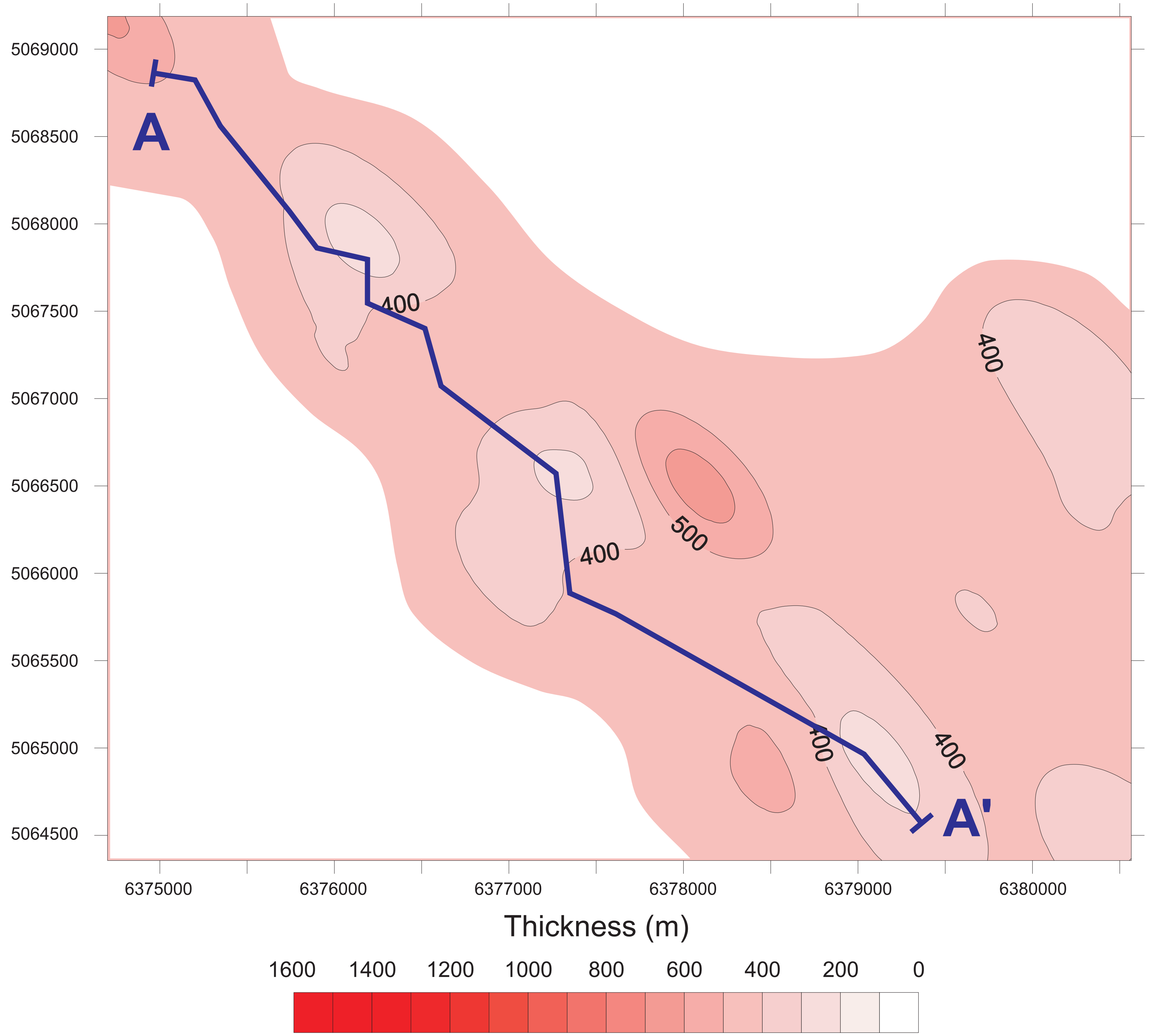
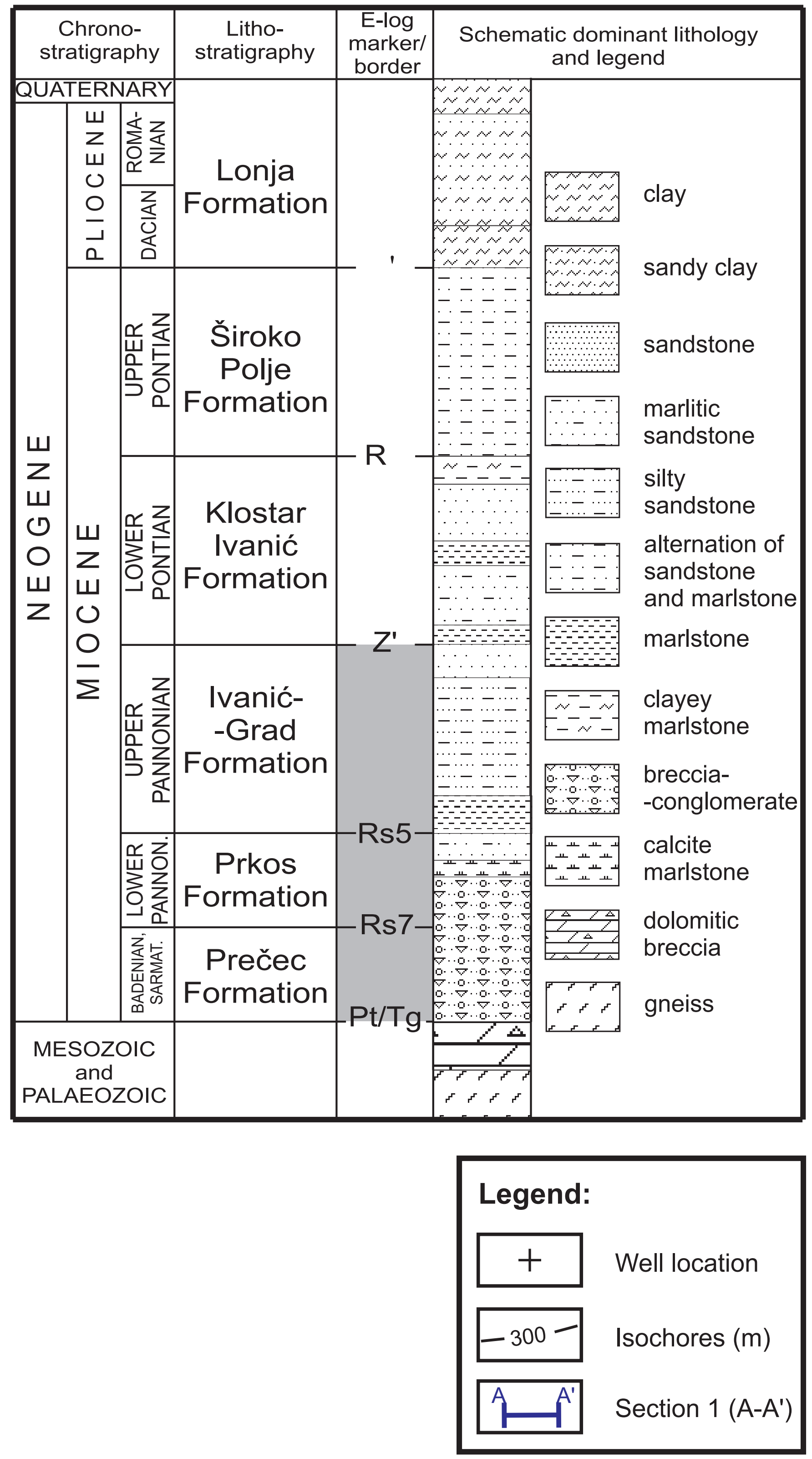
The Kloštar Oil Field is situated at the north-western part of the Sava Depression in the Croatian part of the Pannonian basin (CPBS). Hydrocarbon reservoirs are within Miocene sandstones (upto 1600 m thick) and tectonised Palaeozoic basement schists; it is a typical geological structure that has seen a complex evolution through the Neogene and Quaternary. The structural evolution is reconstructed using palinspastic mapping and presented here as 10 thickness maps.

Map 1:
Thickness map between e-log border “Tg” and marker “Rs5”
(Badenian-Lower Pannonian)



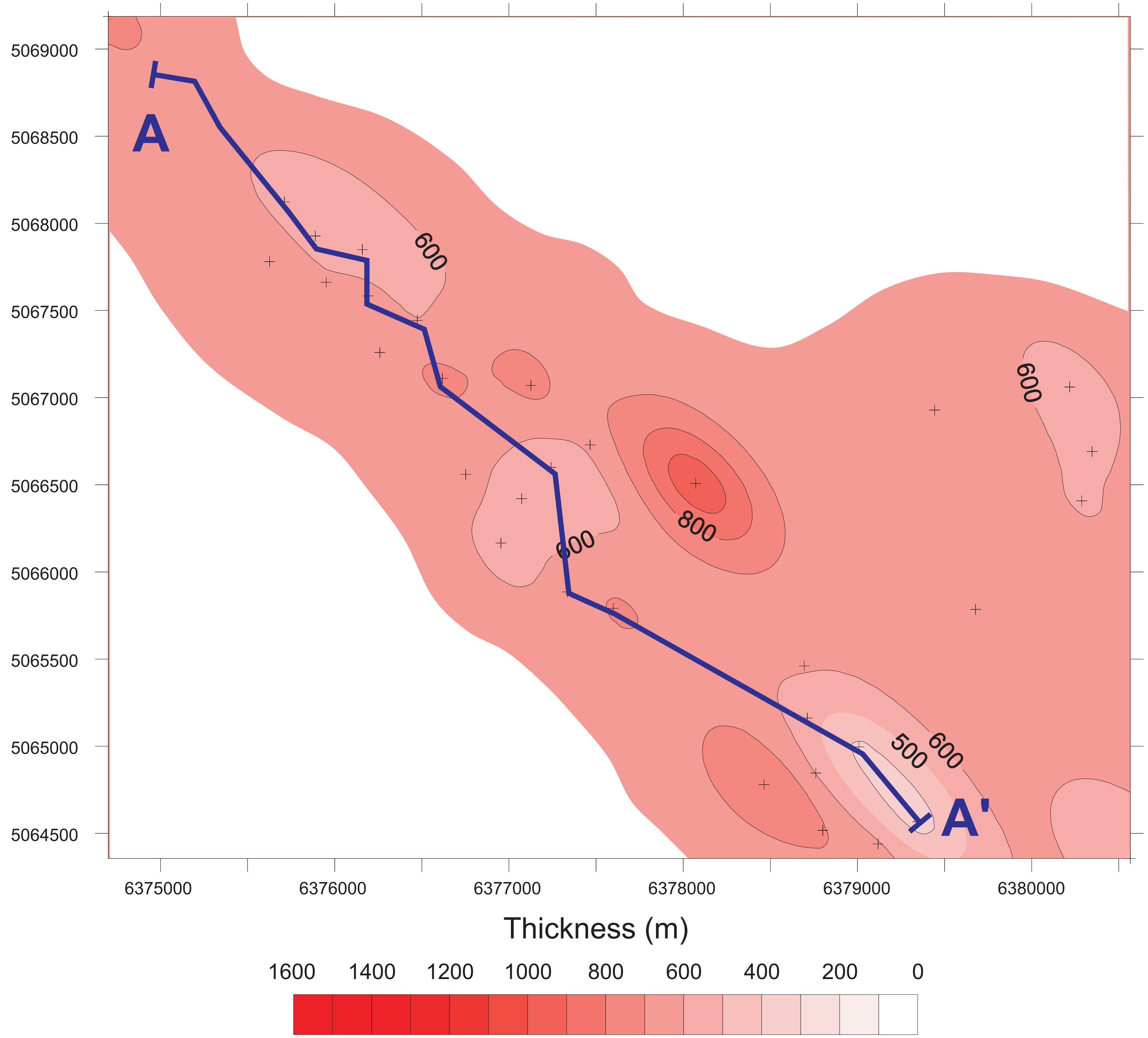
Map 2:
Thickness map between e-log border “Tg” and marker “Z’”
(Badenian-Upper Pannonian)

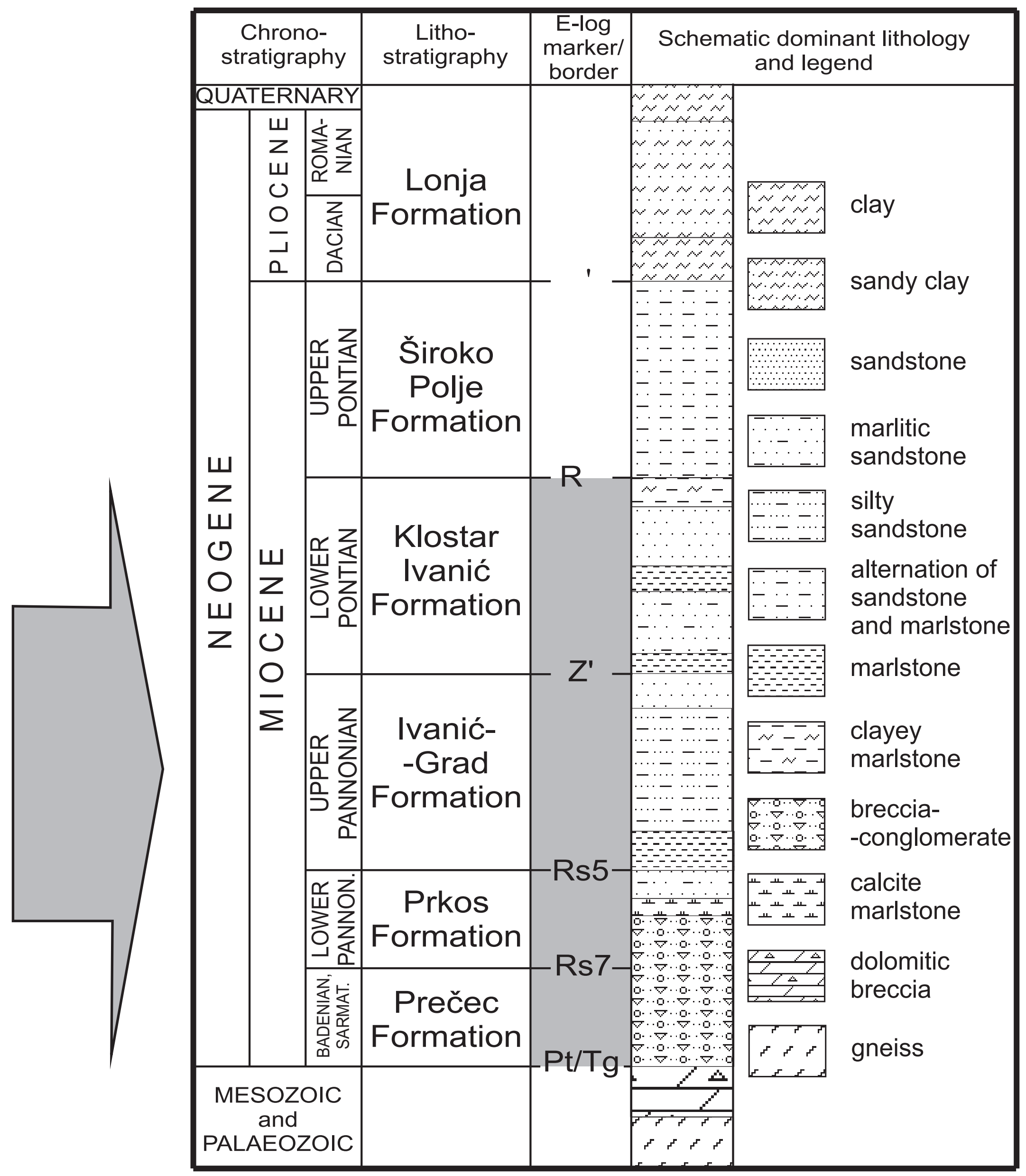




Map 3:

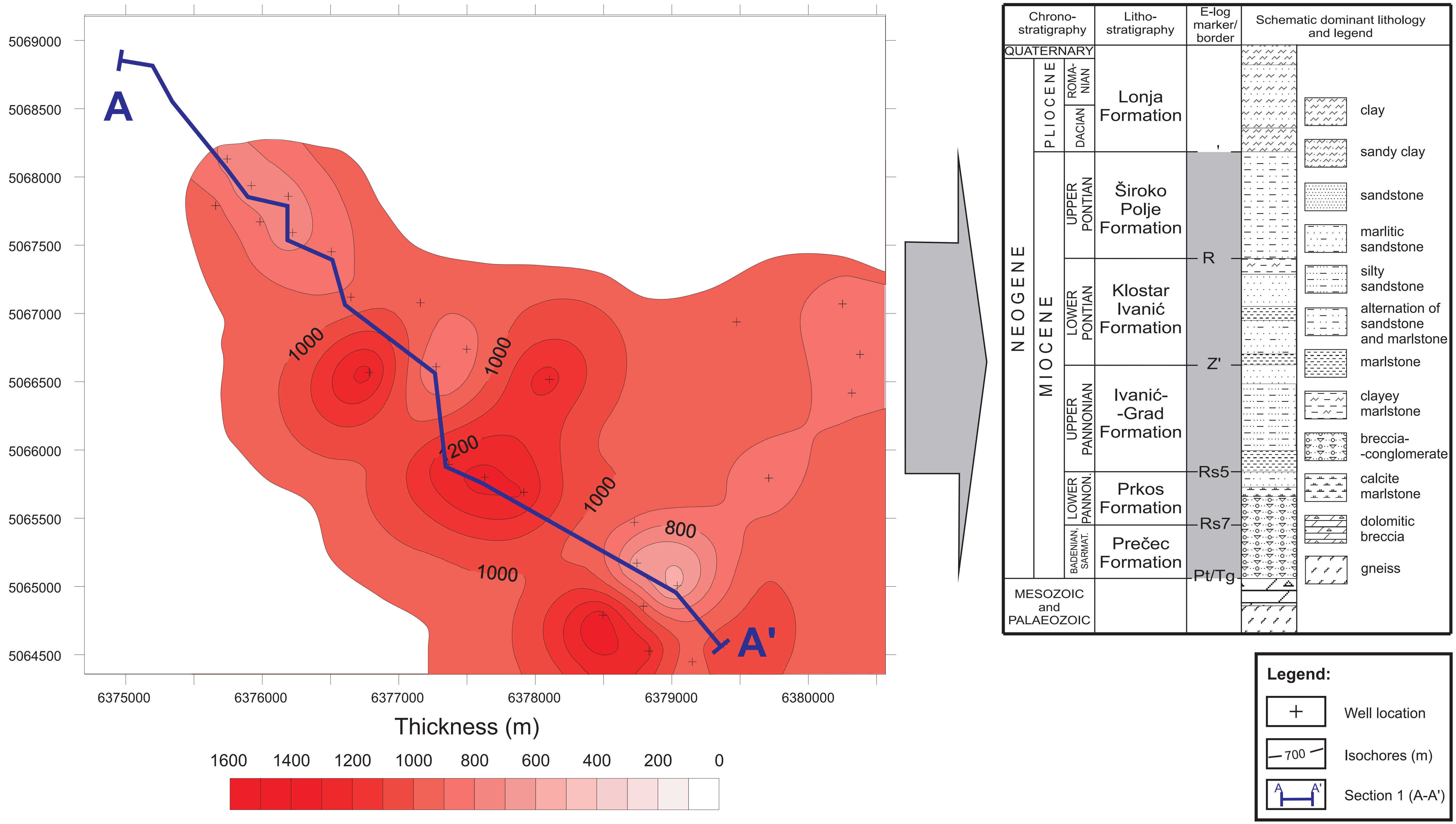
Thickness map between e-log border “Tg” and marker “R ”
(Badenian-Lower Pontian)



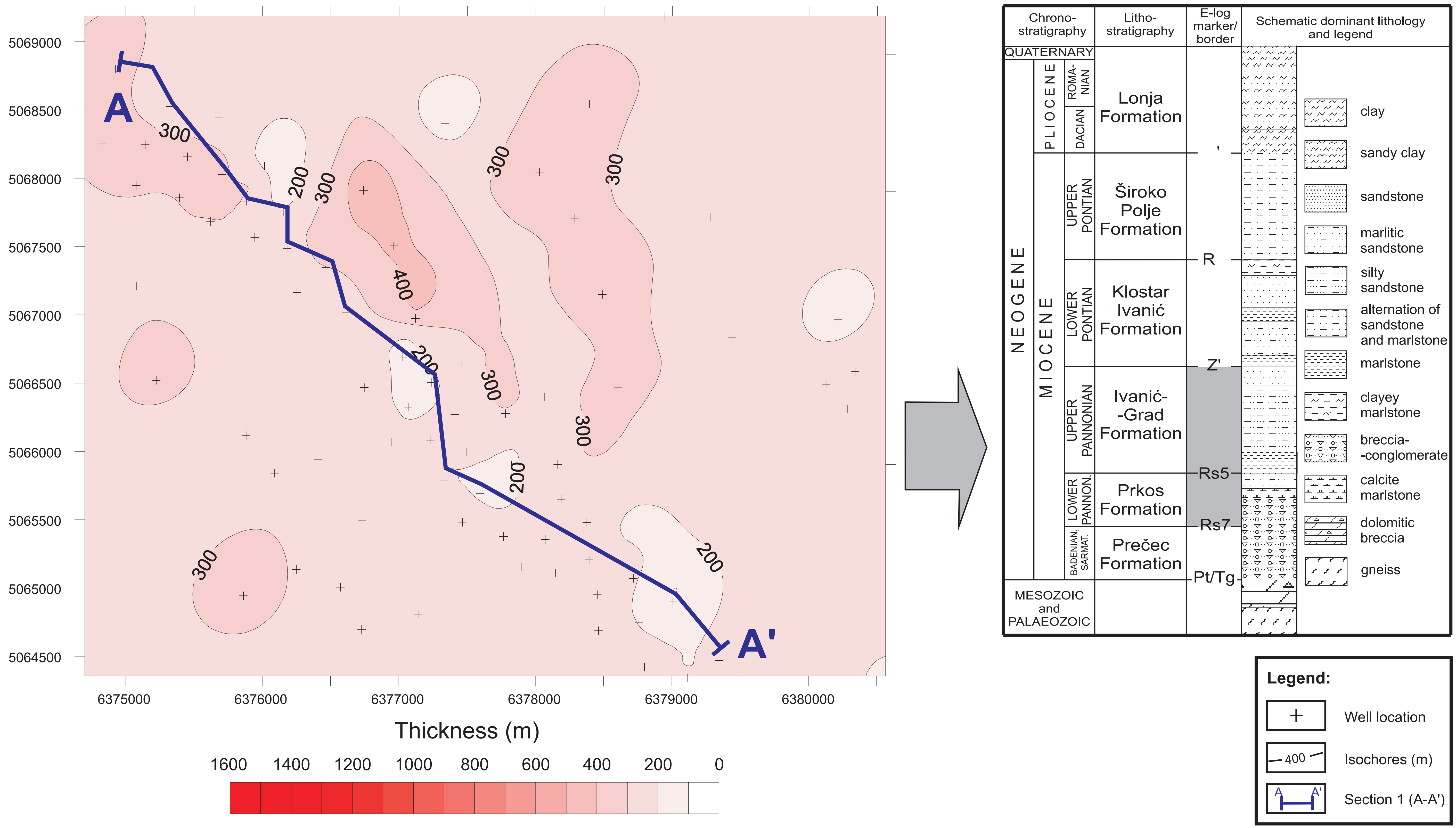


Map 4:

Thickness map between e-log border “Tg” and marker “ ”
(Badenian-Upper Pontian)

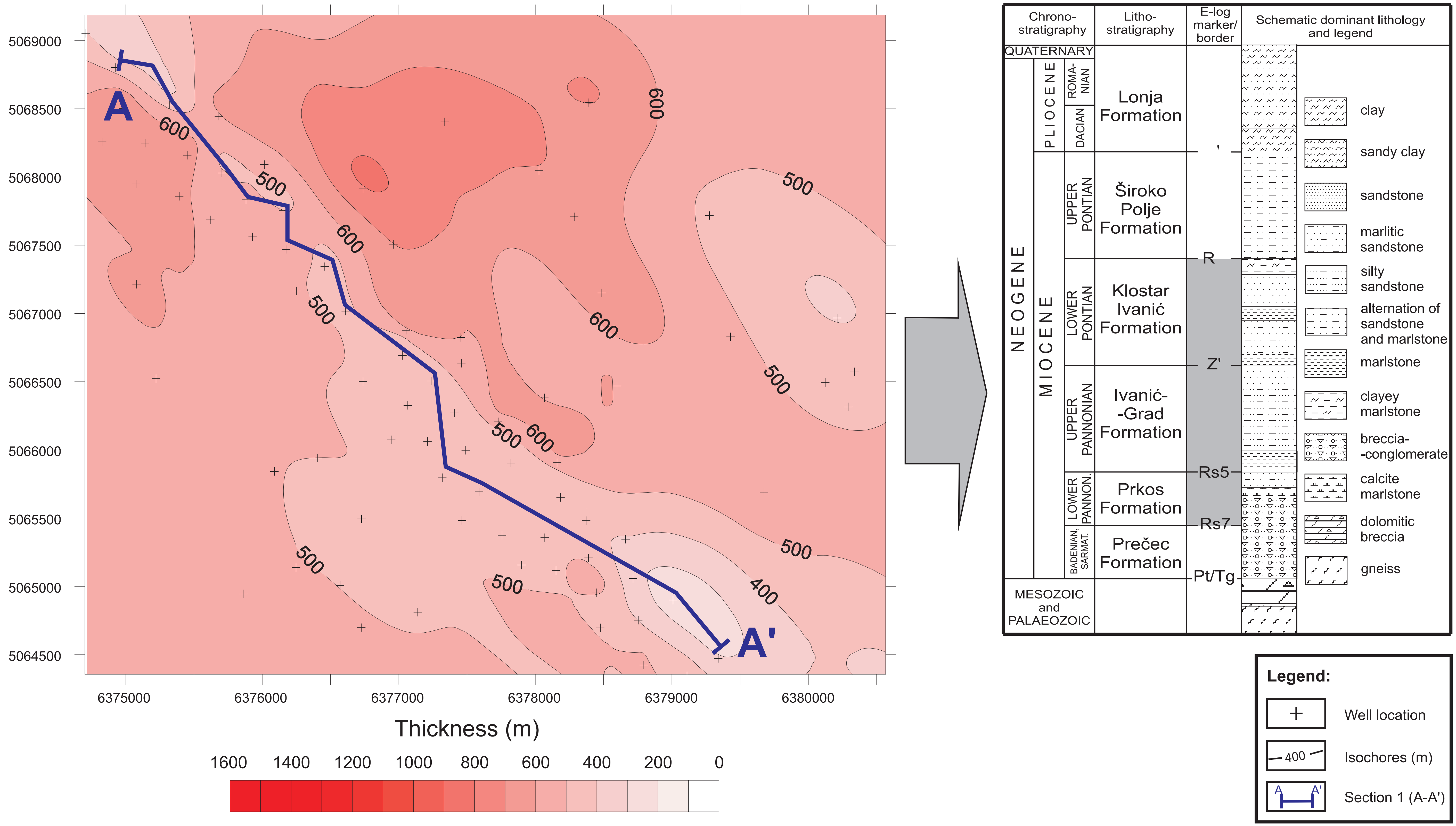


Map 5:
Thickness map between e-log markers “Rs7” and marker “Z'”
(Lower Pannonian-Upper Pannonian)



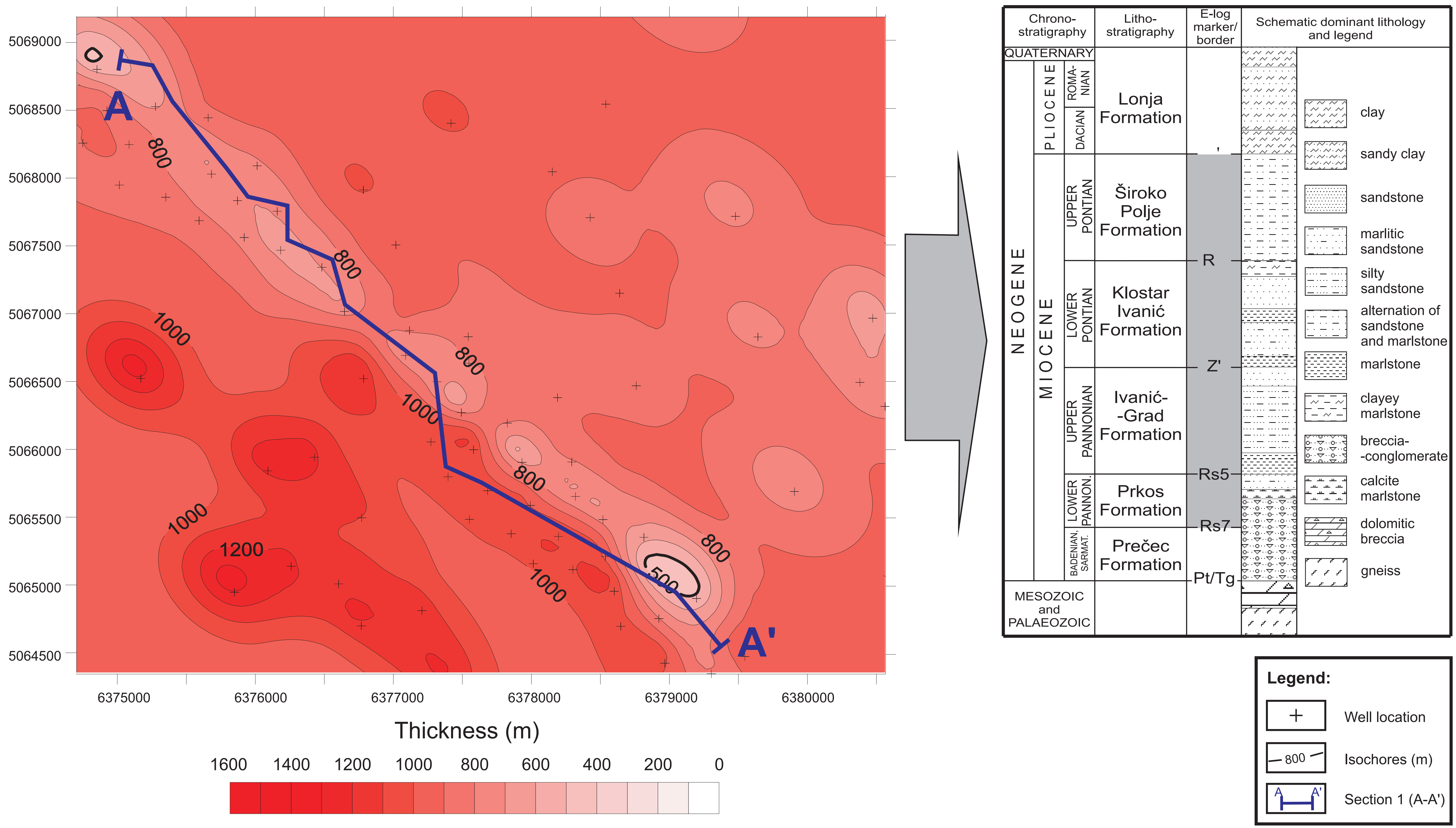
Map 6:

Thickness map between e-log markers “Rs7” and marker “R ”
(Lower Pannonian-Lower Pontian)



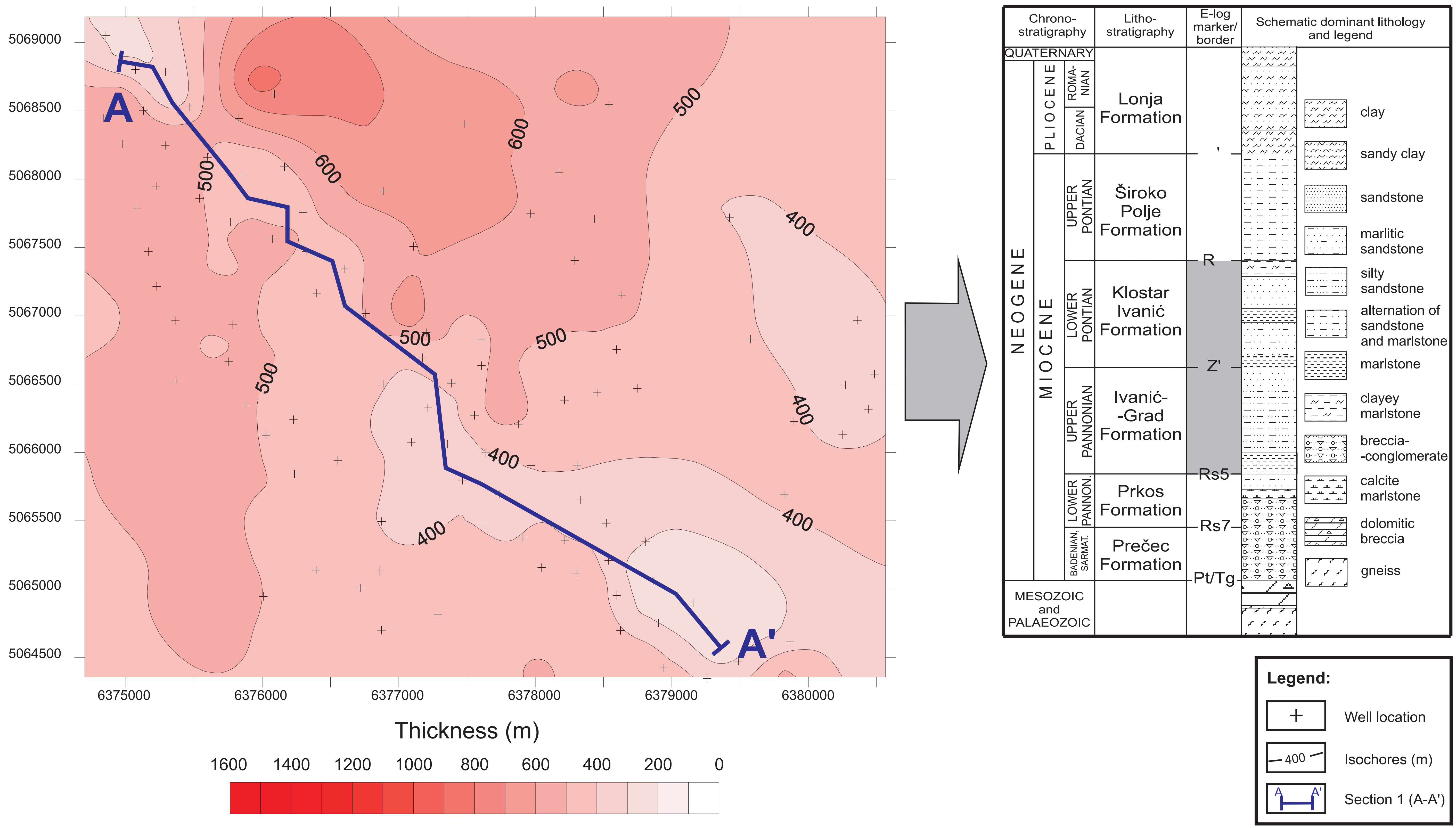
Map 7:

Thickness map between e-log markers “Rs7” and “ '”
(Lower Pannonian-Upper Pontian)



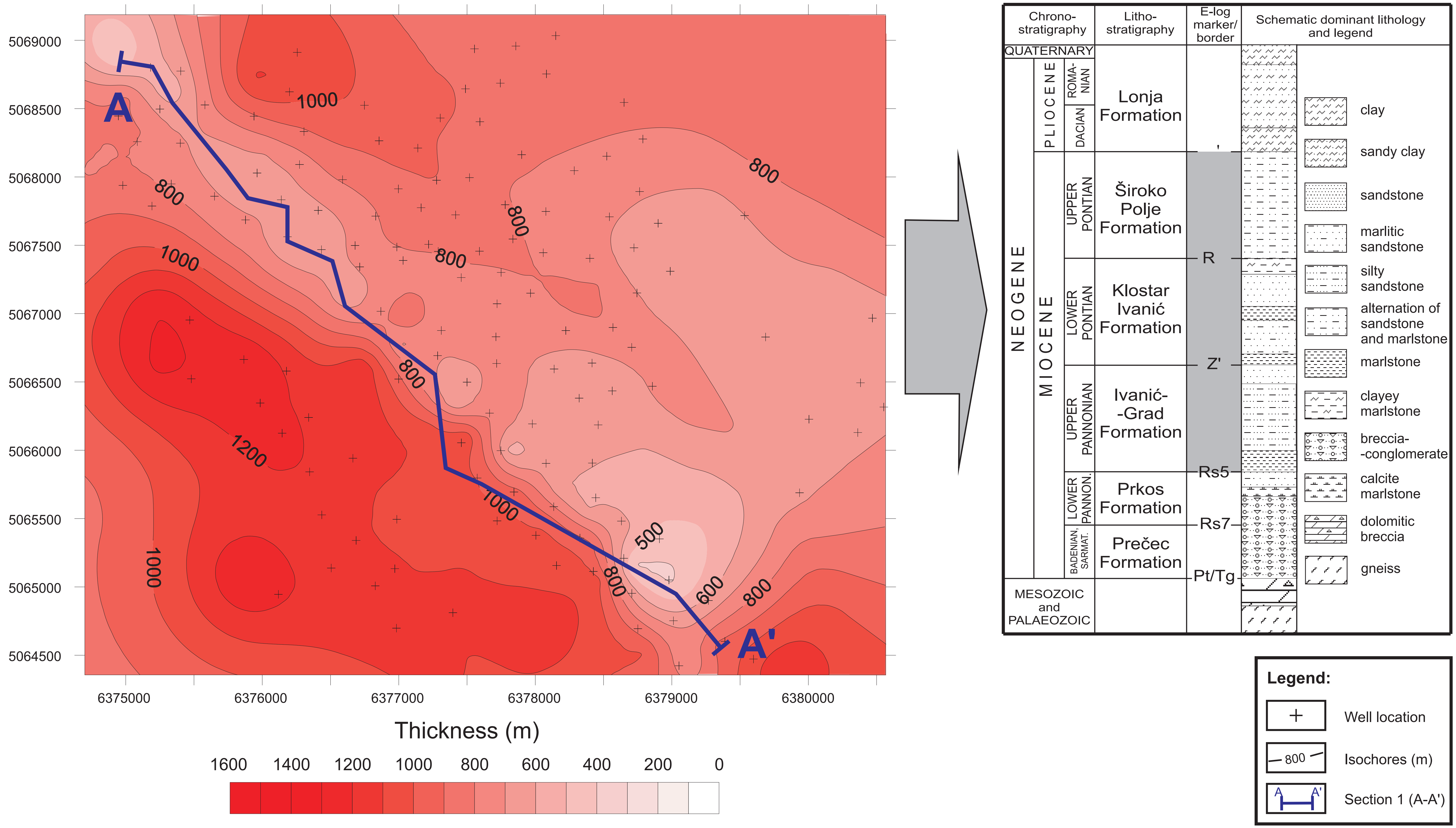
Map 8:

Thickness map between e-log markers “Rs5” and “R ”
(Upper Pannonian-Lower Pontian)



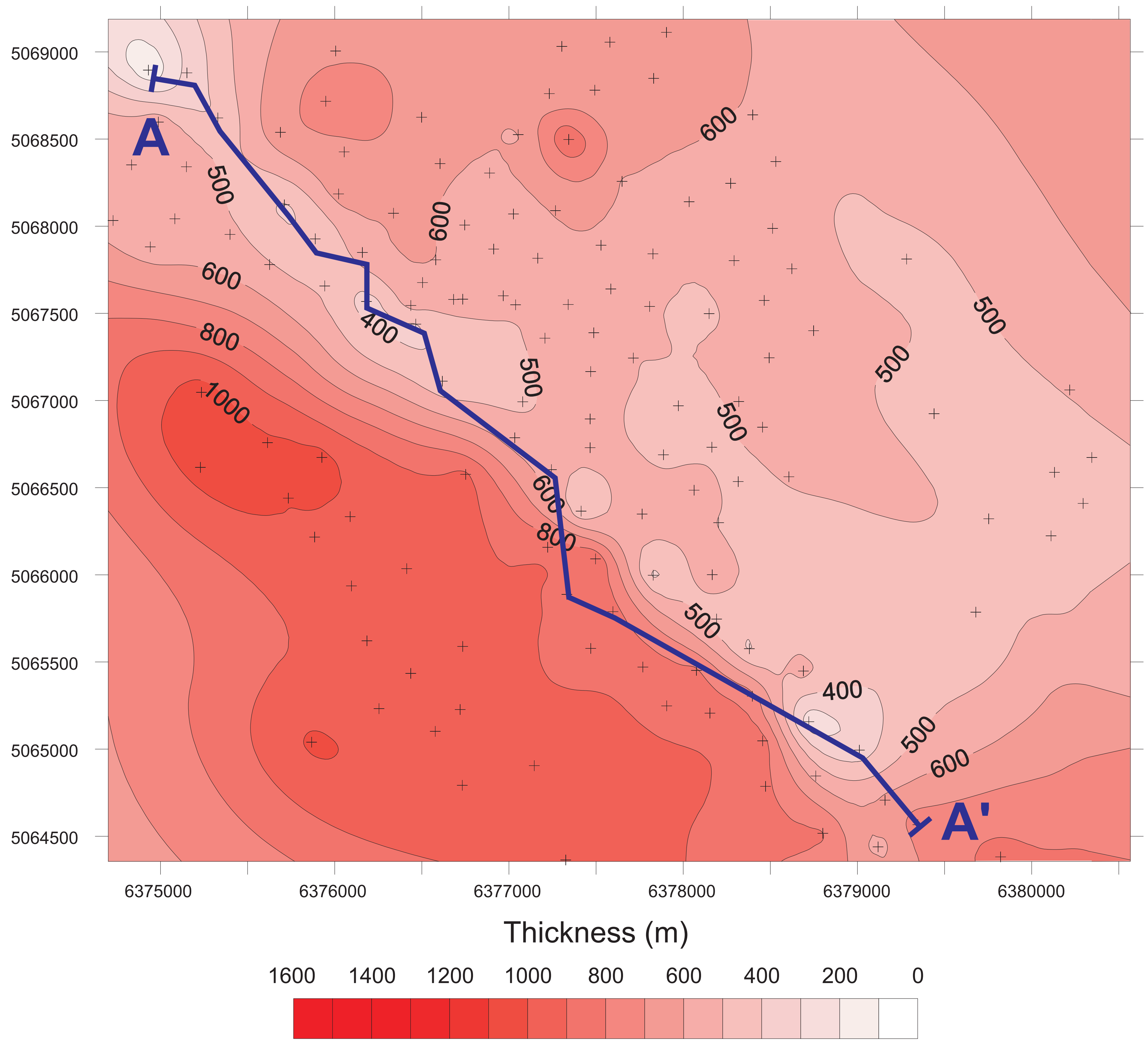
Map 9:

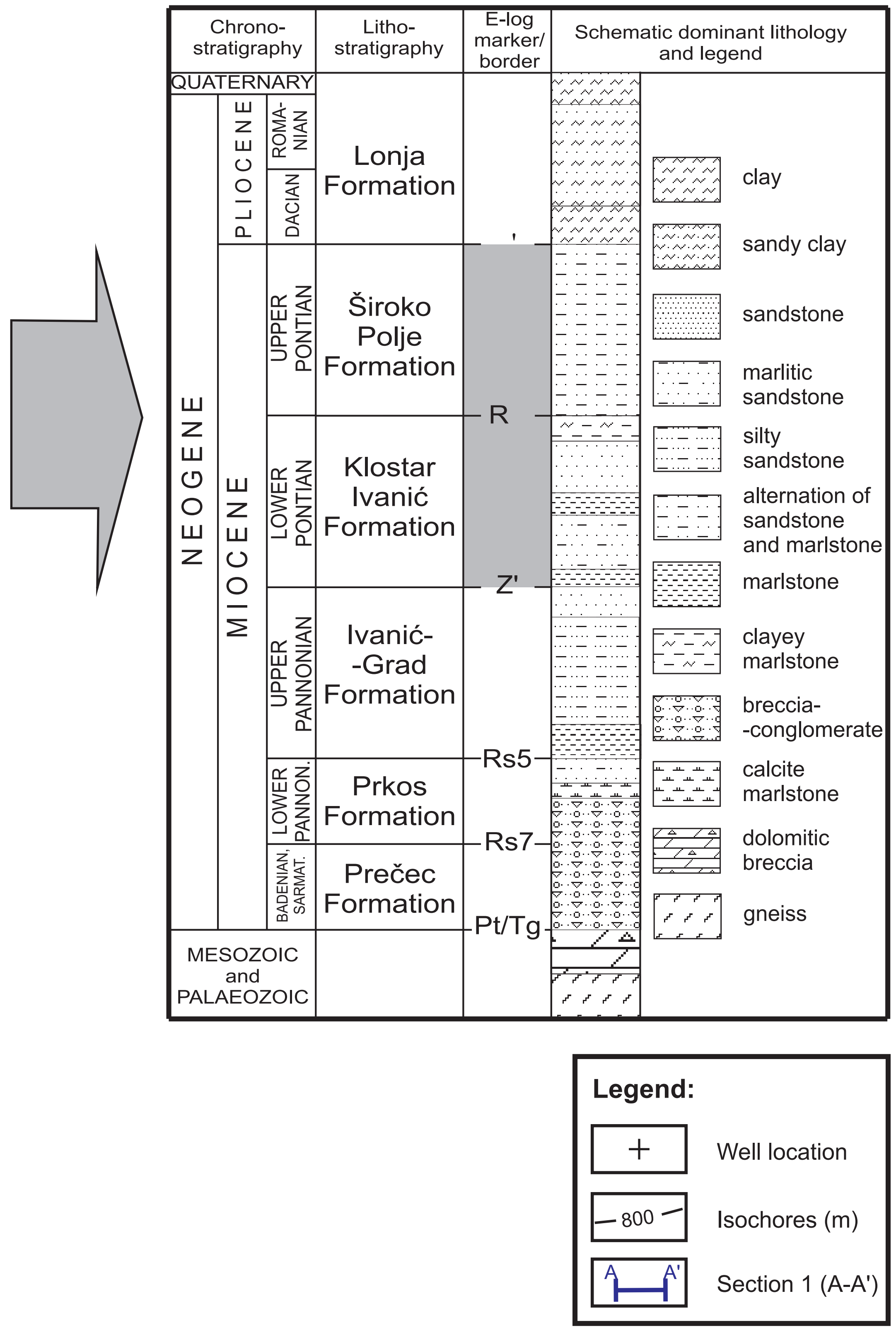
Thickness map between e-log markers “Rs5” and “ ”
(Upper Pannonian-Upper Pontian)



Map 10:

Thickness map between e-log markers “Z'” and “ '”
(Lower Pontian-Upper Pontian)





Section 1:
Palinspastic reconstruction of structural evolution along the Kloštar Field from Badenian to Quaternary